# Constraining Nuclear Structure Physics in CEvNS

Vishvas Pandey

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UF UNIVERSITY of FLORIDA

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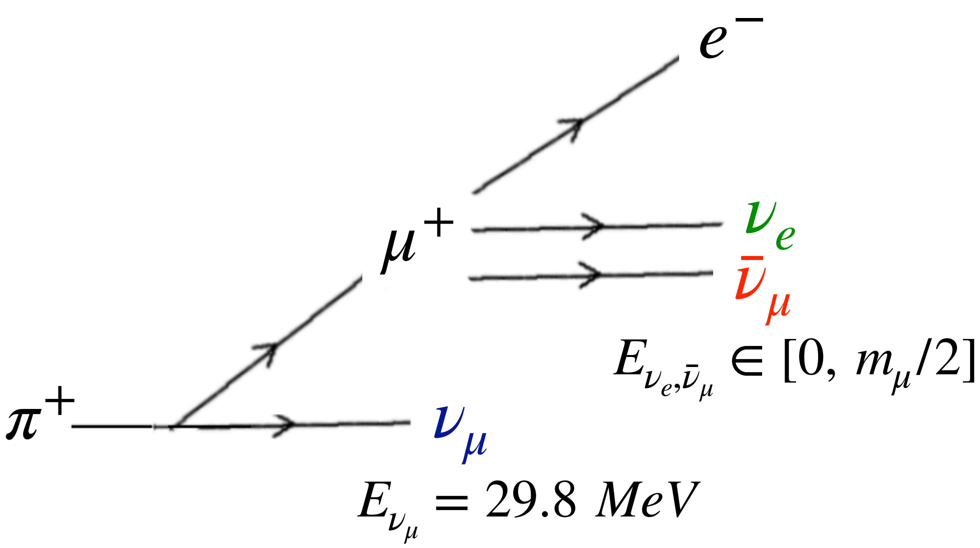
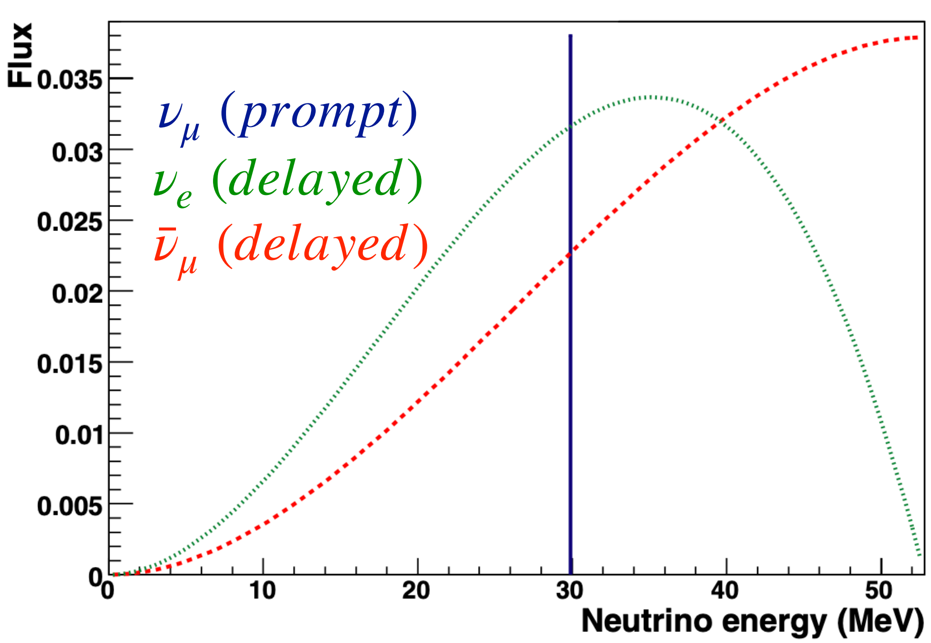
# Constraining Nuclear Structure Physics in CEvNS

## CEvNS: Coherent Elastic Neutrino-Nucleus Scattering

### Neutrino Source




- Pion decay-at-rest



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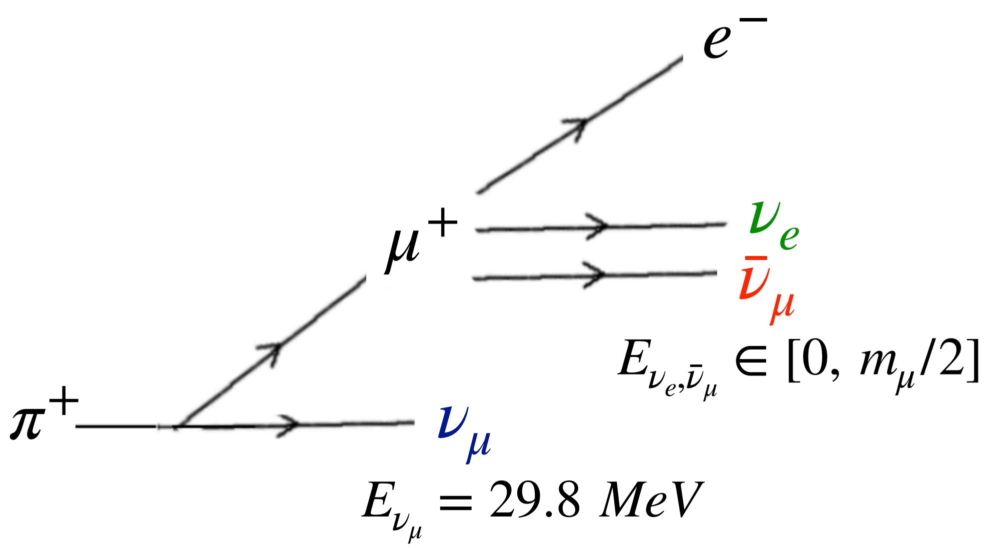


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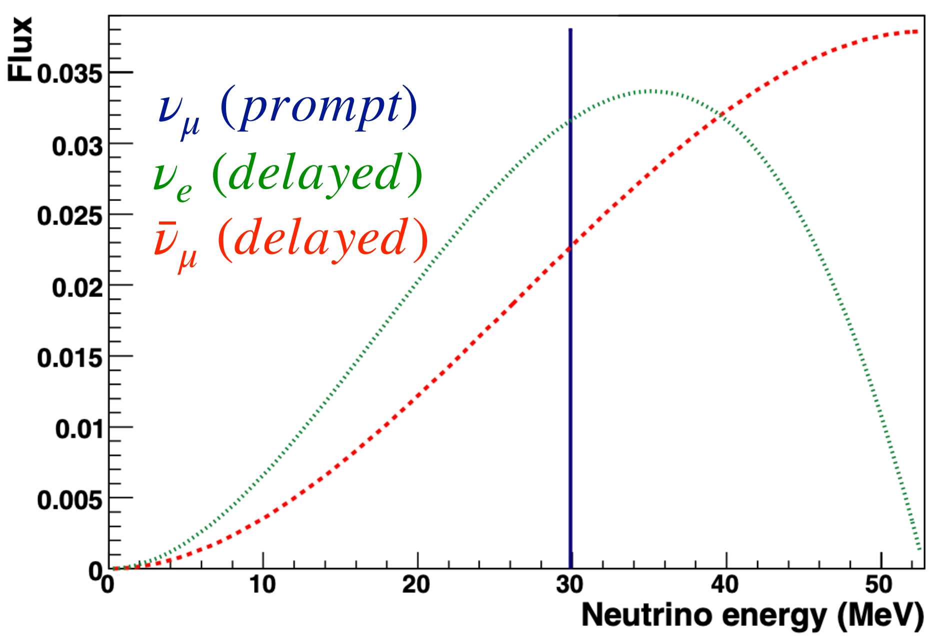
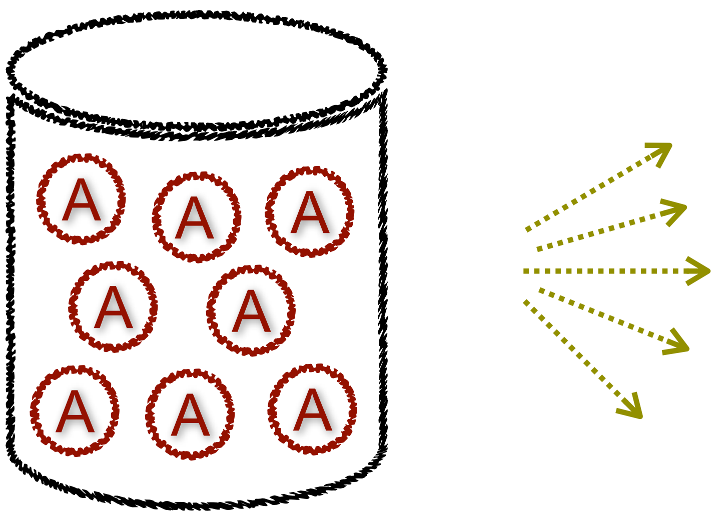



### Detector




- $q \lesssim 1/r$
- Coherent elastic scattering
- Flavor independent

### Signal

~ keV energy nuclear recoil

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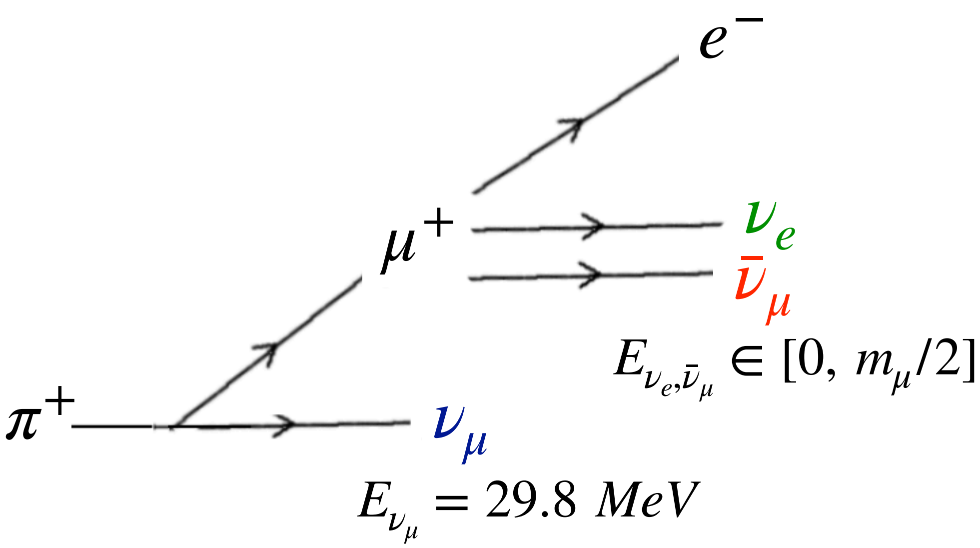


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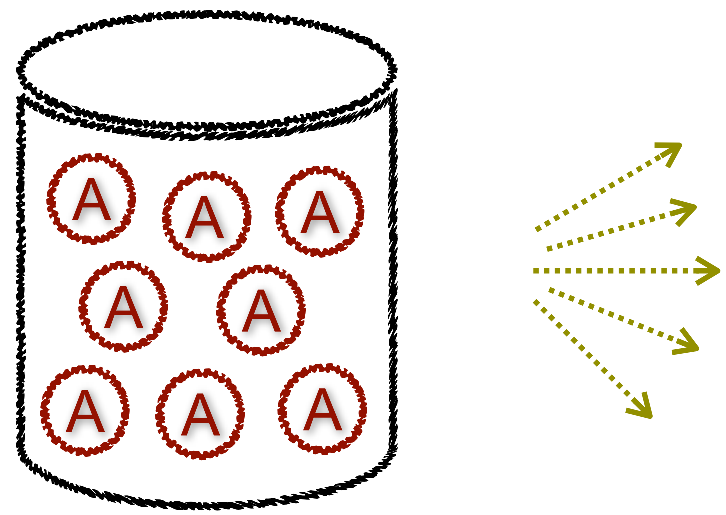


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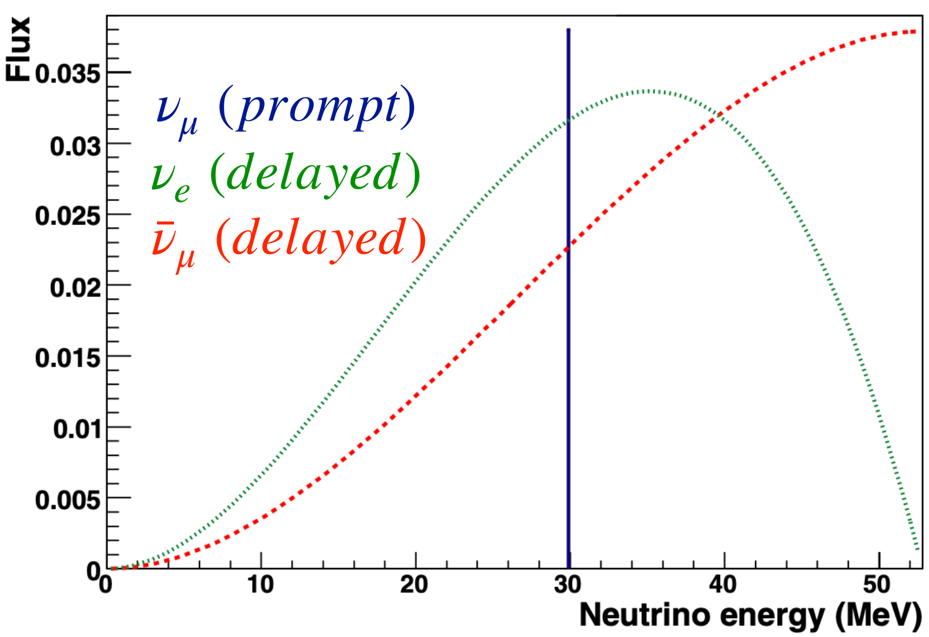


- $q \lesssim 1/r$
- Coherent elastic scattering
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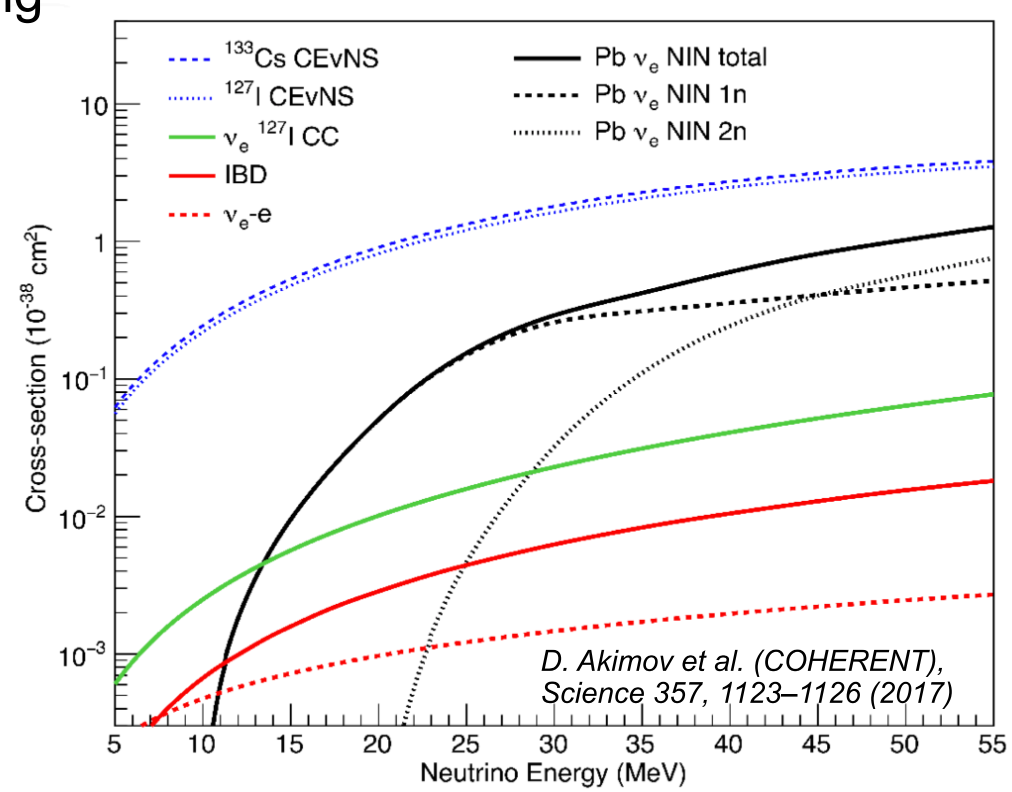
- CEvNS cross section is largest at low energies.



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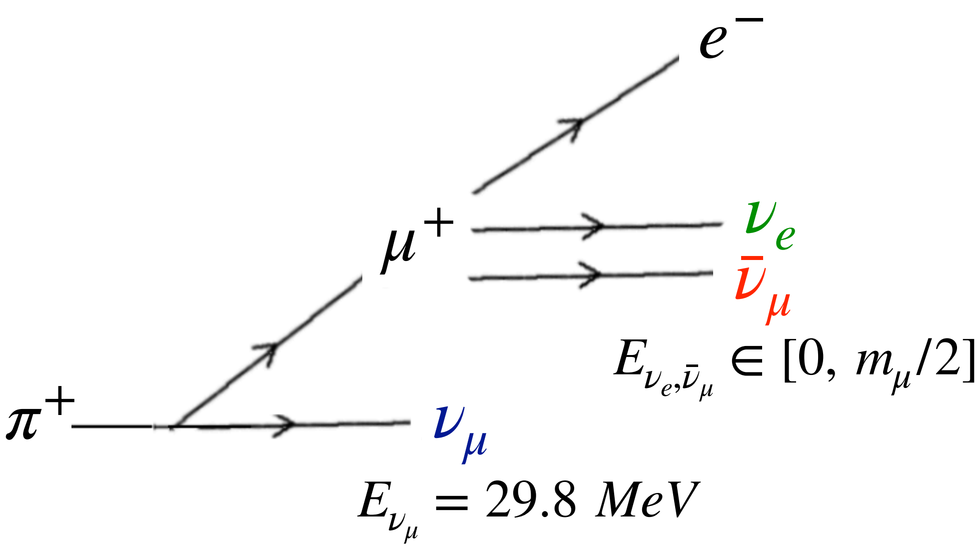


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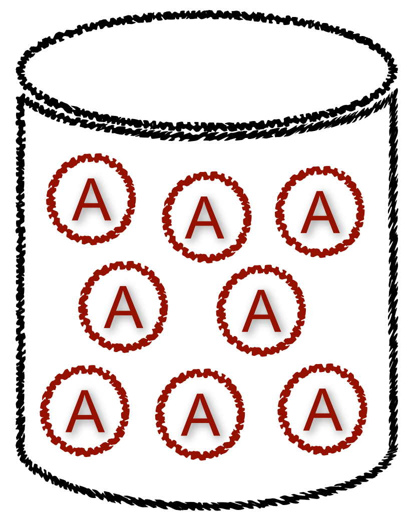


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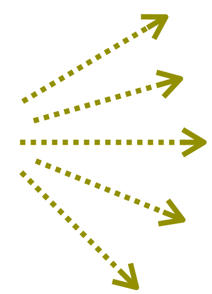


~ keV energy nuclear recoil ($T$)

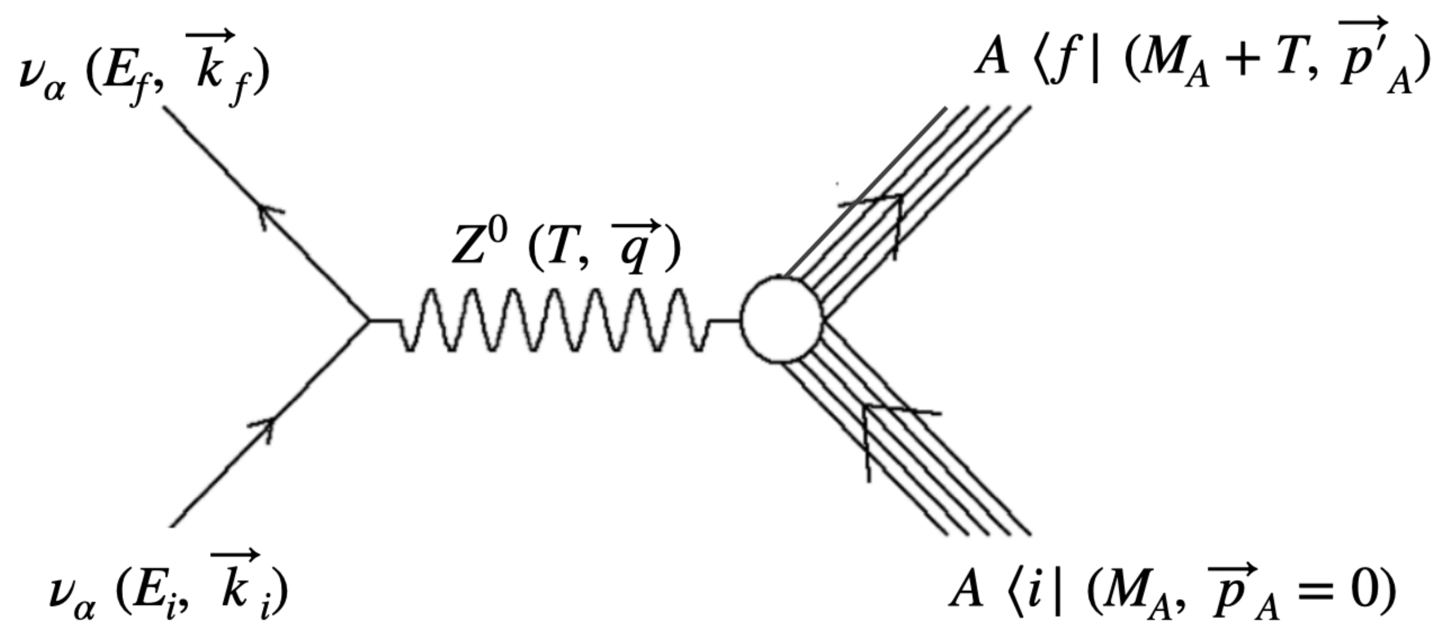
## CEvNS cross section:

Kinematics:

$$T = E_i - E_f$$

$$|\vec{q}\,| = |\vec{k}_i - \vec{k}_f|$$

$$|\vec{p}\,'_A| = \sqrt{(M_A + T)^2 - M_A^2}$$



# Constraining Nuclear Structure Physics in CEvNS

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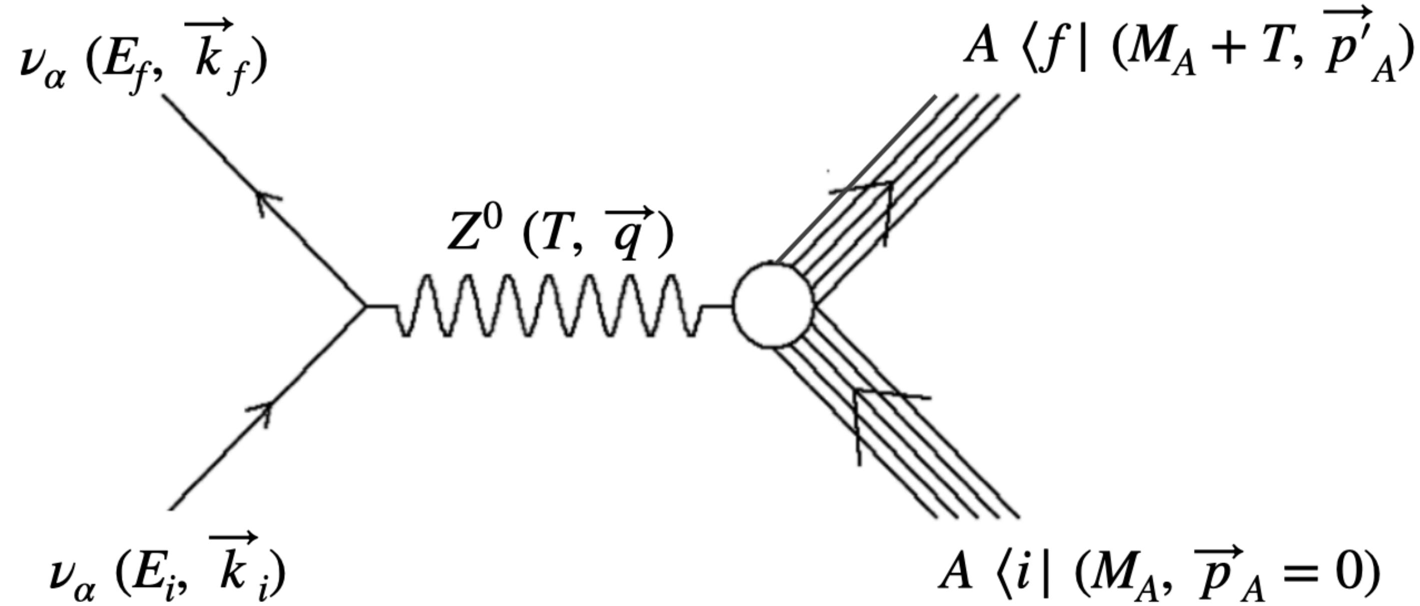
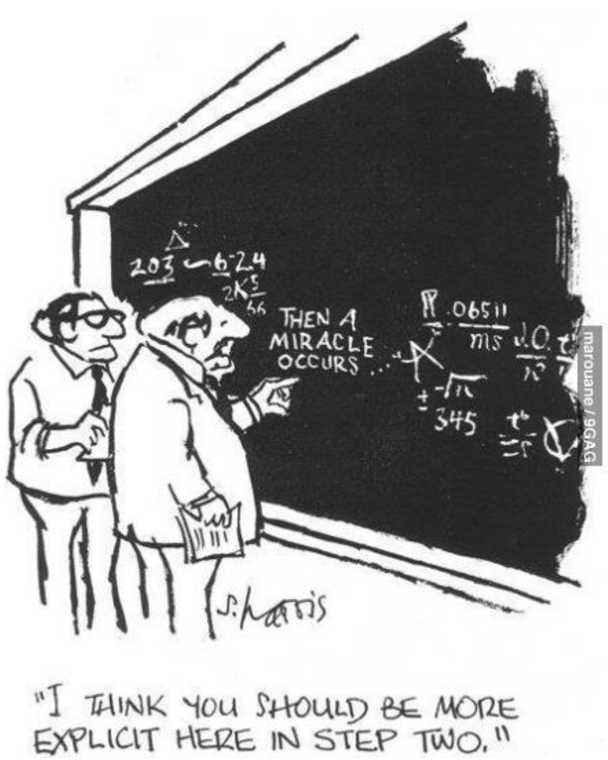



Cross section:

$$\frac{d^6\sigma}{d^3k_f d^3p'_A} \propto \frac{1}{(2\pi)^6}\frac{M_A}{(M_A+T)}\frac{1}{E_iE_F} \times (2\pi)^4 \sum_{fi} |\mathscr{M}|^2 \delta^{(4)}(k_i + p_A - k_f - p'_A)$$



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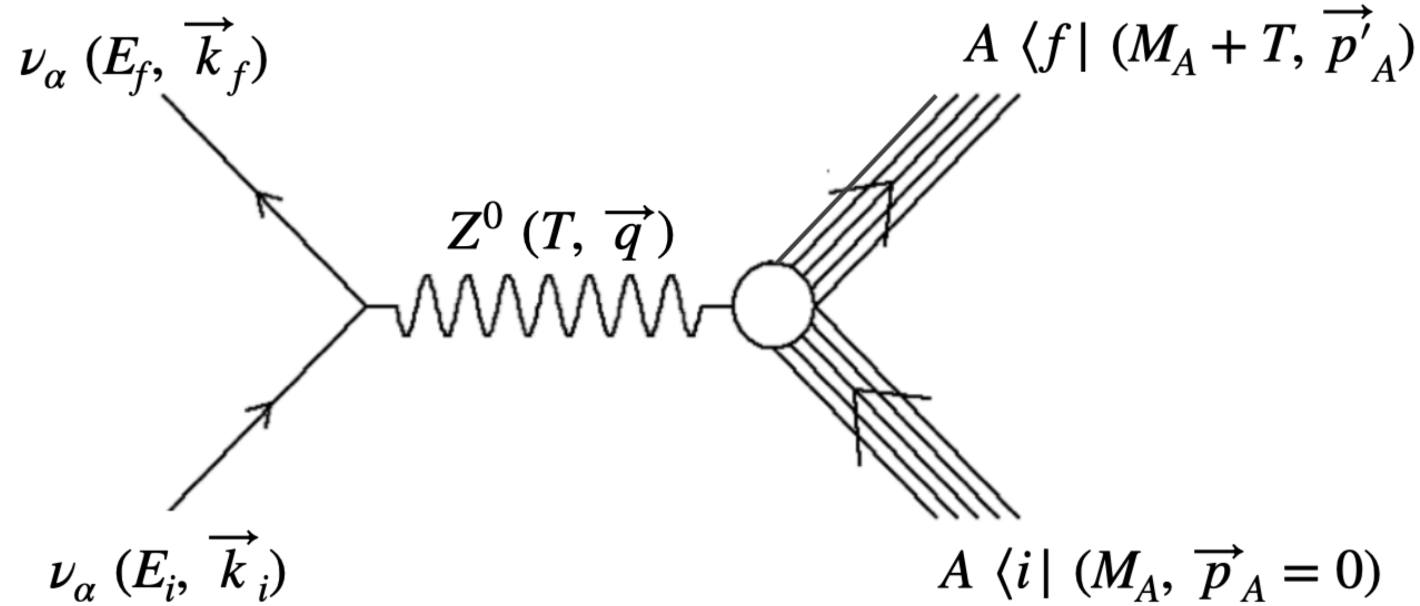


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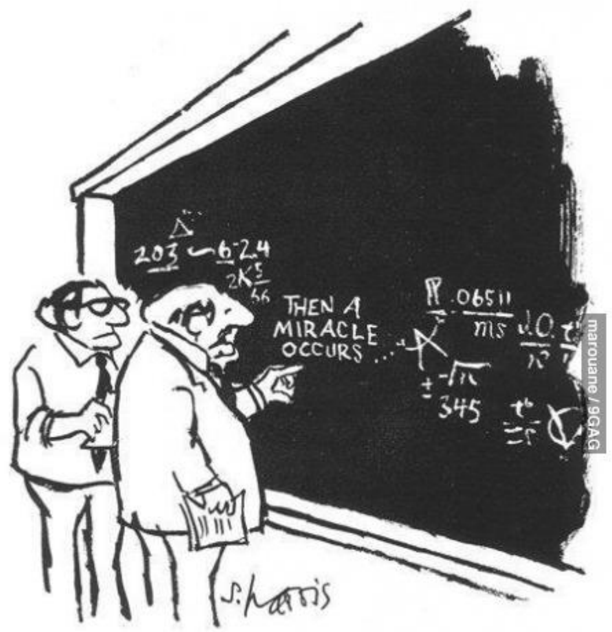
$$\sum_{fi} |\mathscr{M}|^2 \propto \frac{G_F^2}{2} L_{\mu\nu} W^{\mu\nu}$$

Nuclear tensor: $W^{\mu\nu} = \sum_{fi} (\mathscr{J}^\mu_{nucl})^\dagger \mathscr{J}^\nu_{nucl}$

Nuclear current transition amplitude: $\mathscr{J}^\mu_{nucl} = \langle \Phi_0 | \hat{J}^\mu(\vec{q}) | \Phi_0 \rangle$

Elastic scattering on a spherically symmetric nuclei ($J^\pi = 0^+$): $\approx \frac{Q_W}{2} F_W(q)$




"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

# Constraining Nuclear Structure Physics in CEvNS

CEvNS cross section:

$$\boxed{\frac{d\sigma}{d\cos\theta_f} = \frac{G_F^2}{2\pi}E_i^2(1+\cos\theta_f)\,\frac{Q_W^2}{4}F_W^2(q)}$$

$$\boxed{\frac{d\sigma}{dT} = \frac{G_F^2}{\pi}M_A\left[1-\frac{T}{E_i}-\frac{M_A T}{2E_i^2}\right]\frac{Q_W^2}{4}F_W^2(q)}$$

- In CEvNS process, the entire nuclear structure and dynamics is encoded in the weak form factor $F_W(q)$.

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- In CEvNS process, the entire nuclear structure and dynamics is encoded in the weak form factor $F_W(q)$.

$$\boxed{F_W(q) = \frac{1}{Q_W}\left[\left(1 - 4\sin^2\theta_W\right) Z\, F_p(q) - N\, F_n(q)\right]}$$

Proton (charge) form factor: proton densities and charge form factors are relatively well constrained through decades of elastic electron scattering experiments.

Neutron form factor: neutron densities and form factors are only poorly known. Note that CEvNS is primary sensitive to neutron density distributions.

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Neutron form factor: neutron densities and form factors are only poorly known. Note that CEvNS is primary sensitive to neutron density distributions.

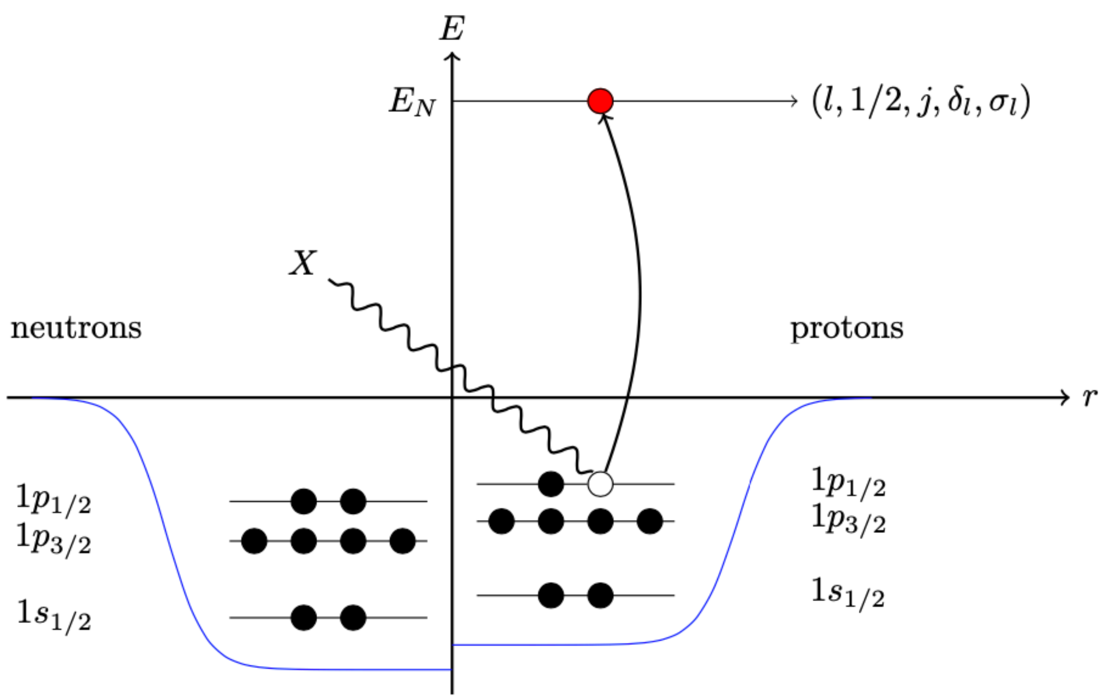
✦ The neutron density distributions and weak nuclear form factors have to be theoretically modeled to evaluate the CEvNS cross section and event rates.

✦ The accuracy of such modeling is vital to the CEvNS program since any experimentally measured deviation from the expected CEvNS event rate can point to *new physics* or to *unconstrained nuclear physics*.

# Constraining Nuclear Structure Physics in CEvNS

## Calculating Form Factors from Nuclear Structure Physics

- A microscopic many–body nuclear theory model: **HF-SkE2**
- Nuclear ground state is described as a many-body quantum mechanical system where nucleons are bound in a realistic nuclear potential.
- Solve Hartree-Fock (**HF**) equation with a Skyrme (**SkE2**) nuclear potential to obtain single–nucleon wave functions for the bound nucleons in the nuclear ground state. Fill up nuclear shells following Pauli principle.



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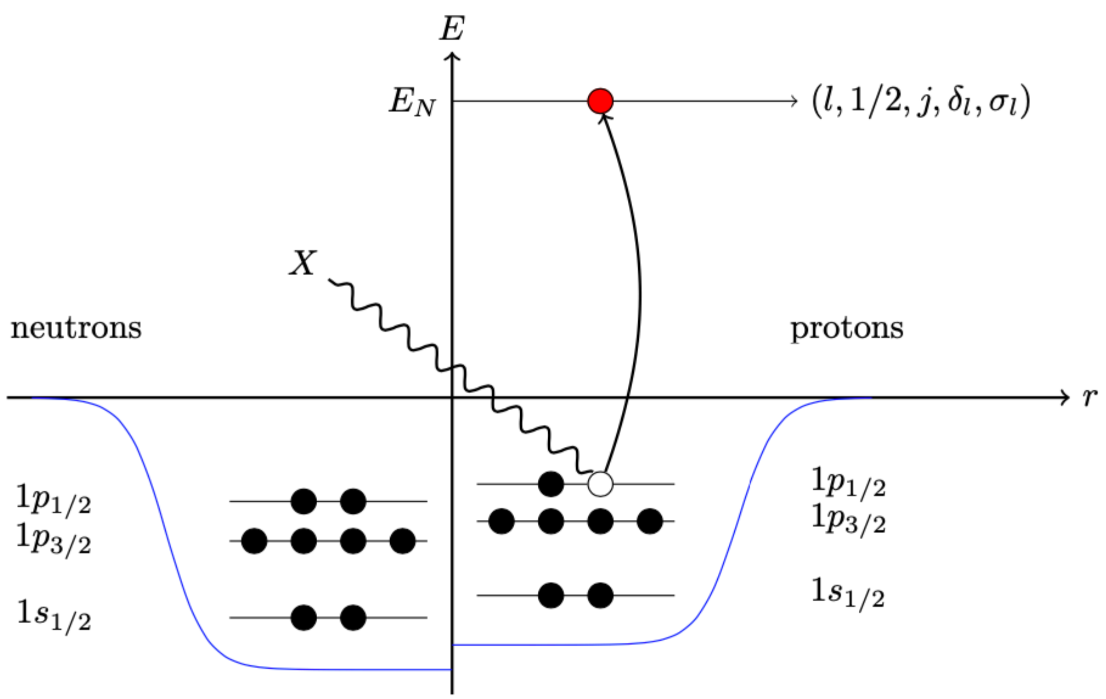
- Evaluate proton and neutron density distributions from those wave functions:

$$\boxed{\rho_i(r) = \frac{1}{4\pi r^2} \sum_a v_{a,i}^2 (2j_a + 1)\, |\, \phi_{a,i}(r)\, |^2} \quad (i = p, n)$$



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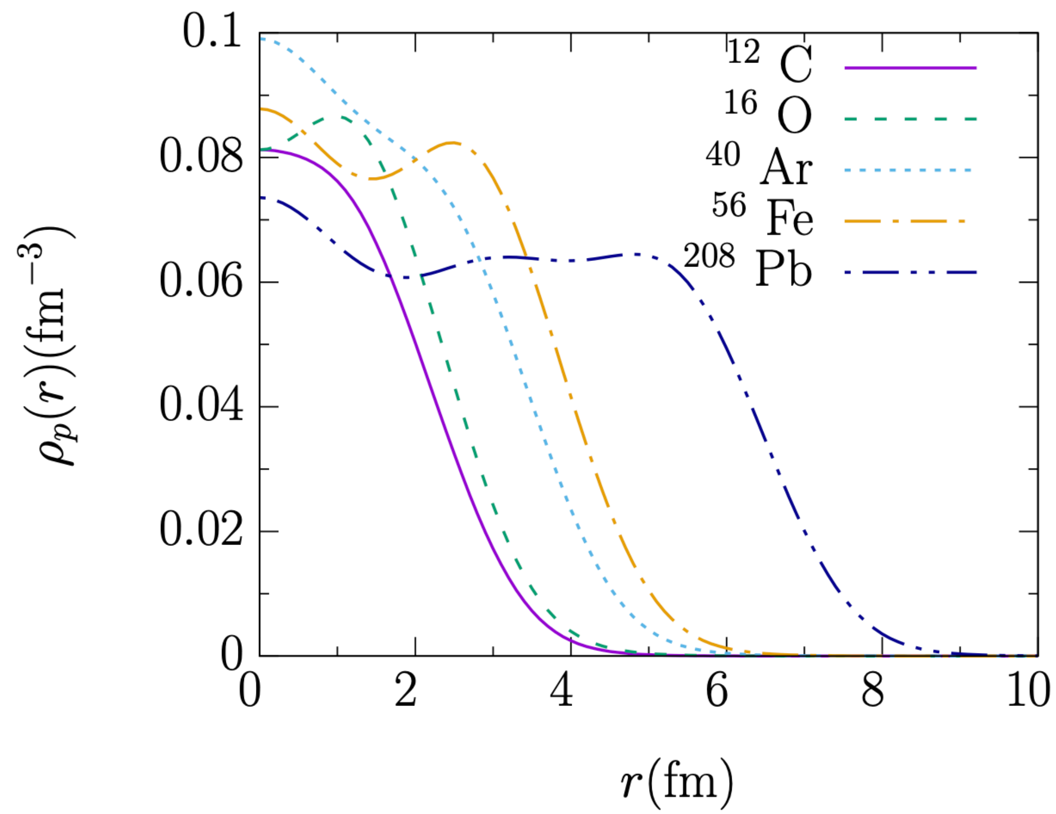


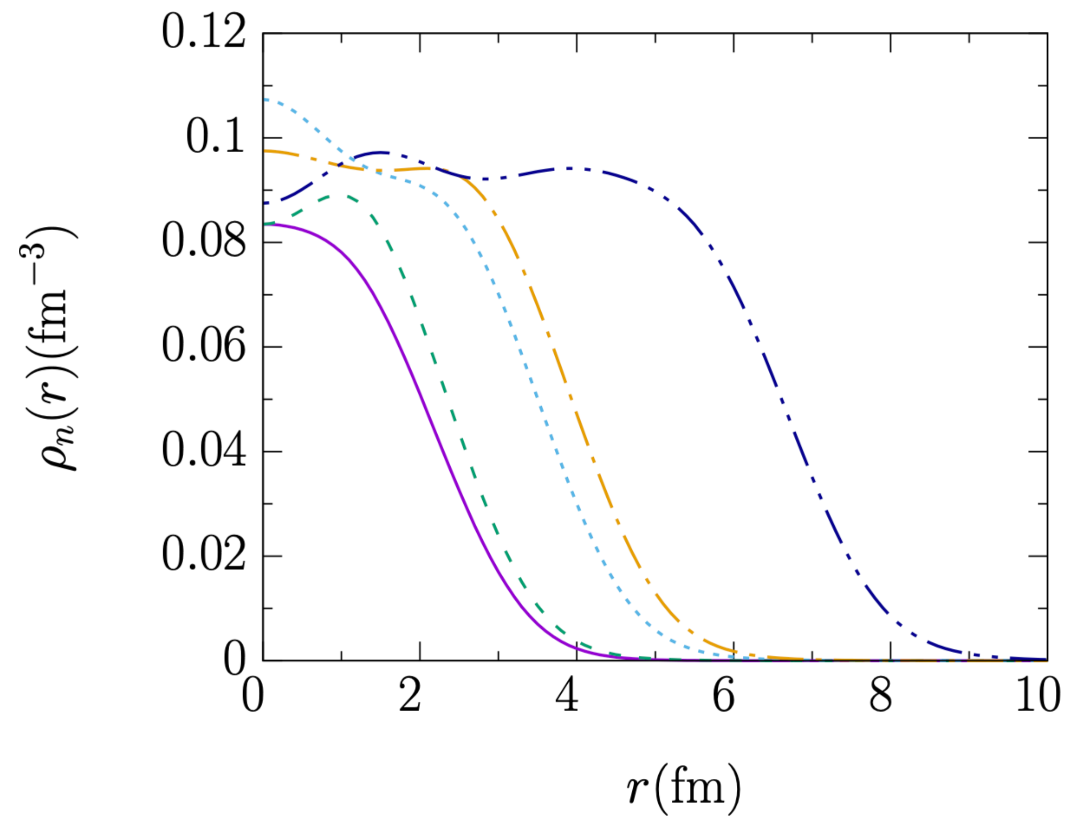


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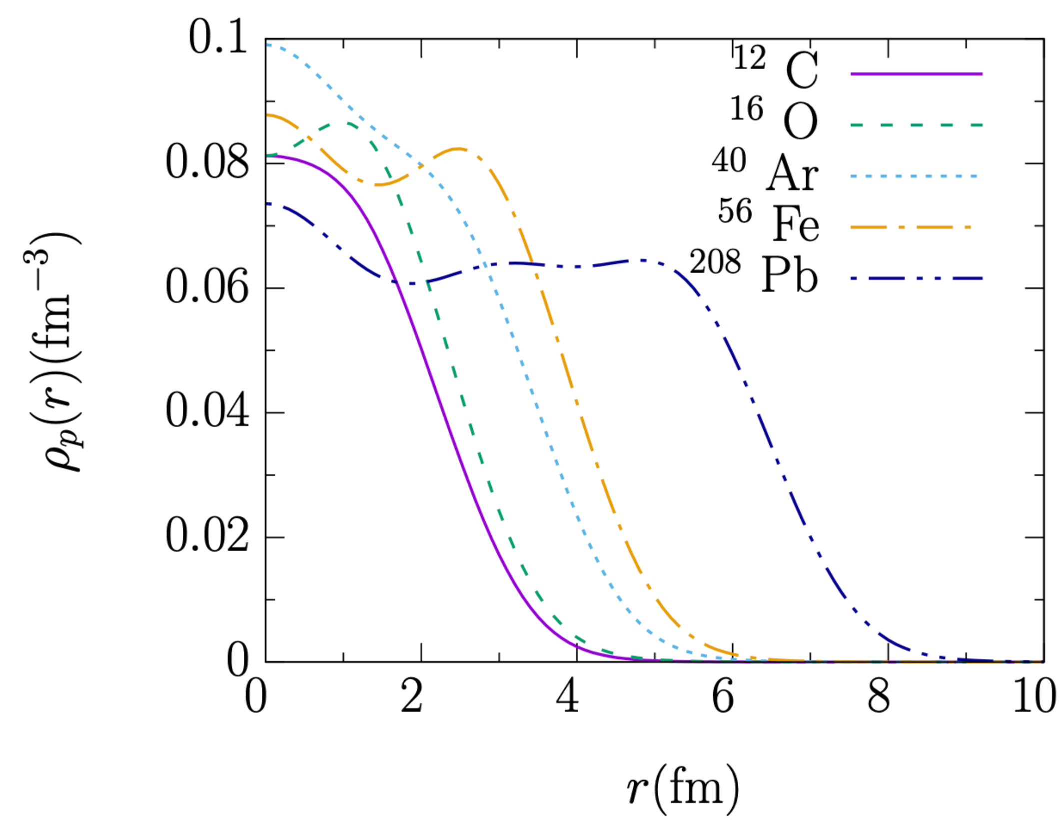
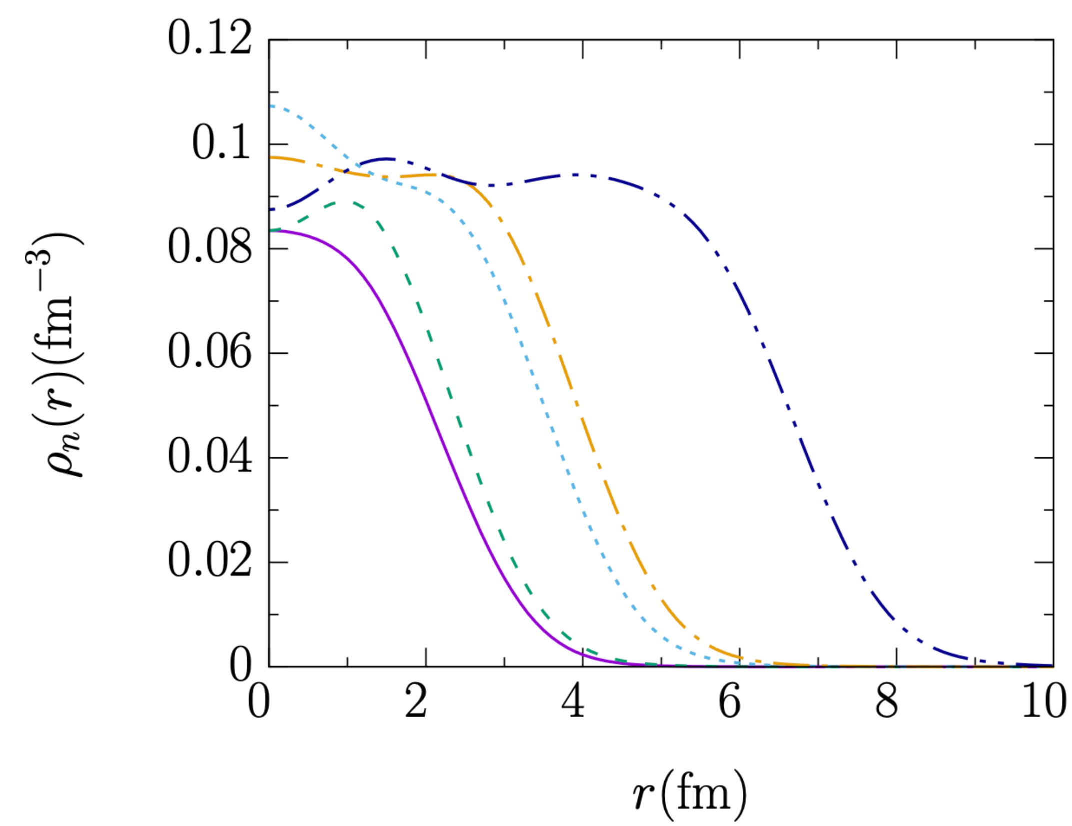
- The proton and neutron densities are utilized to calculate proton and neutron form factors:

$$\boxed{\begin{aligned} F_n(q) &= \frac{4\pi}{N} \int dr \; r^2 \, \frac{\sin(qr)}{qr} \, \rho_n(r) \\ F_p(q) &= \frac{4\pi}{Z} \int dr \; r^2 \, \frac{\sin(qr)}{qr} \, \rho_p(r) \end{aligned}}$$

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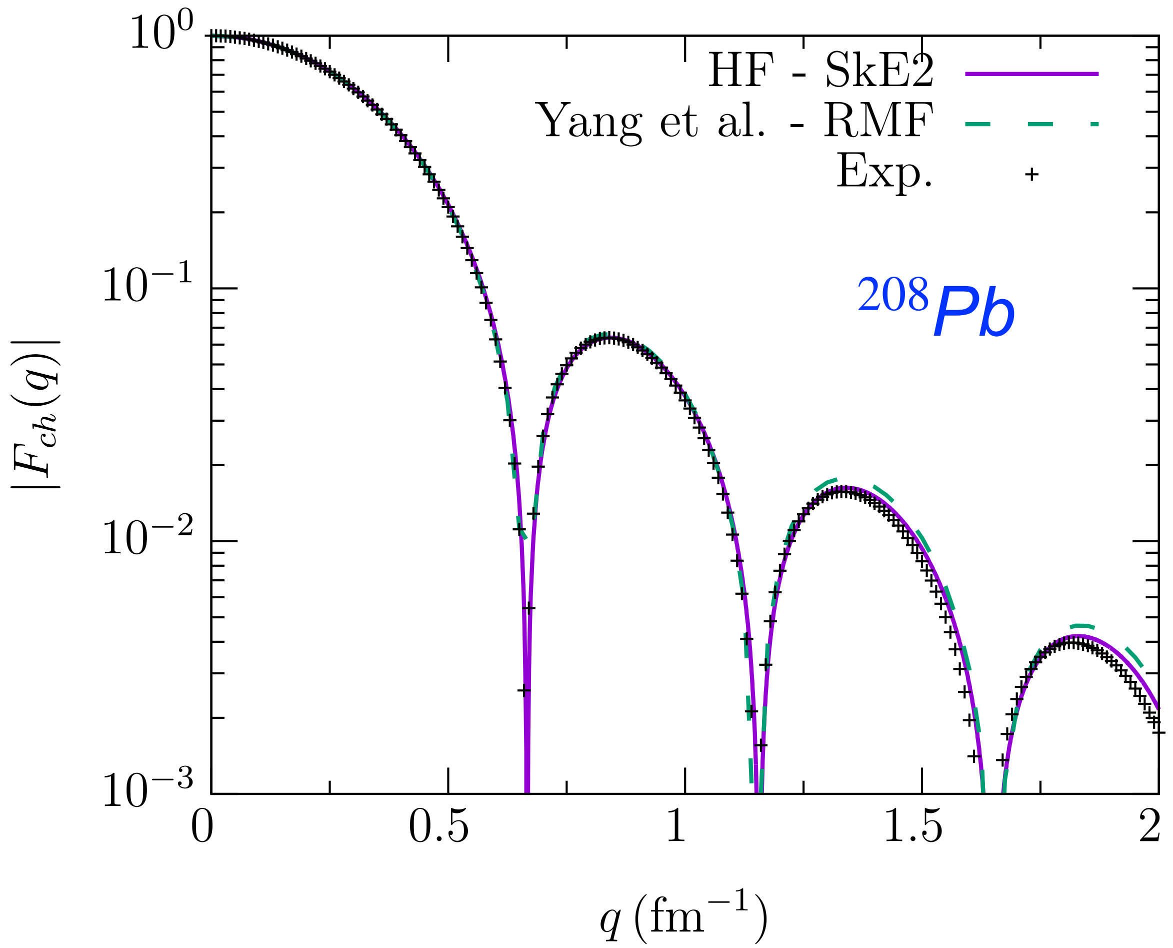
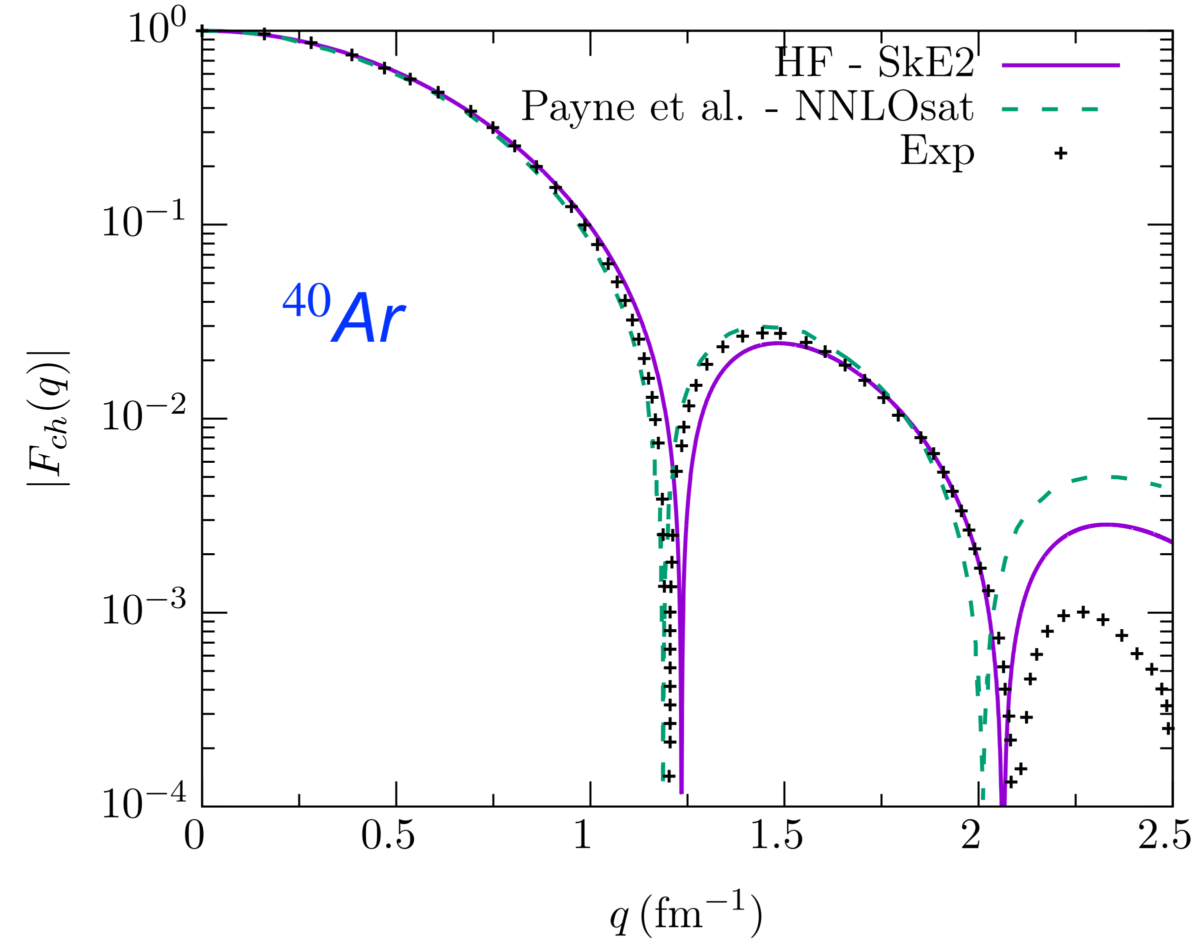
## Charge Form Factor




- *HF-SkE2 (this work): arXiv:2007.03658 [nucl-th]*
- *RMF: Yang et al., Phys. Rev. C 100, 054301 (2019)*
- *Experimental Data: H. De Vries, et al., Atom. Data Nucl. Data Tabl. 36, 495 (1987)*

- *HF-SkE2 (this work): arXiv:2007.03658 [nucl-th]*
- *$NNLO_{sat}$: Payne et al., Phys. Rev. C 100, 061304 (2019)*
- *Experimental Data: C. R. Ottermann et al., Nucl. Phys. A 379, 396 (1982).*

- Our charge form factor predictions of $^{208}$Pb and $^{40}$Ar describe the elastic electron scattering experimental data remarkably well.
- For energies relevant for pion decay–at–rest neutrinos, the region above q = 0.5 fm$^{-1}$ does not contribute to CEvNS cross section.

# Constraining Nuclear Structure Physics in CEvNS

- **Focusing on $^{40}$Ar:** To quantify differences between different weak form factors and CEvNS cross section predictions due to different underlying nuclear structure details, we plot relative differences between 6 different theoretical predictions, arbitrarily using HF–SkE2 as a reference calculation.

$$|\Delta F_{\mathrm{W}}^{i}(q)| = \frac{|F_{\mathrm{W}}^{i}(q) - F_{\mathrm{W}}^{\mathrm{HF}}(q)|}{|F_{\mathrm{W}}^{\mathrm{HF}}(q)|}$$

$$\Delta \sigma_{\mathrm{W}}^{i}(E) = \frac{|\sigma_{\mathrm{W}}^{i}(E) - \sigma_{\mathrm{W}}^{\mathrm{HF}}(E)|}{\sigma_{\mathrm{W}}^{\mathrm{HF}}(E)}$$

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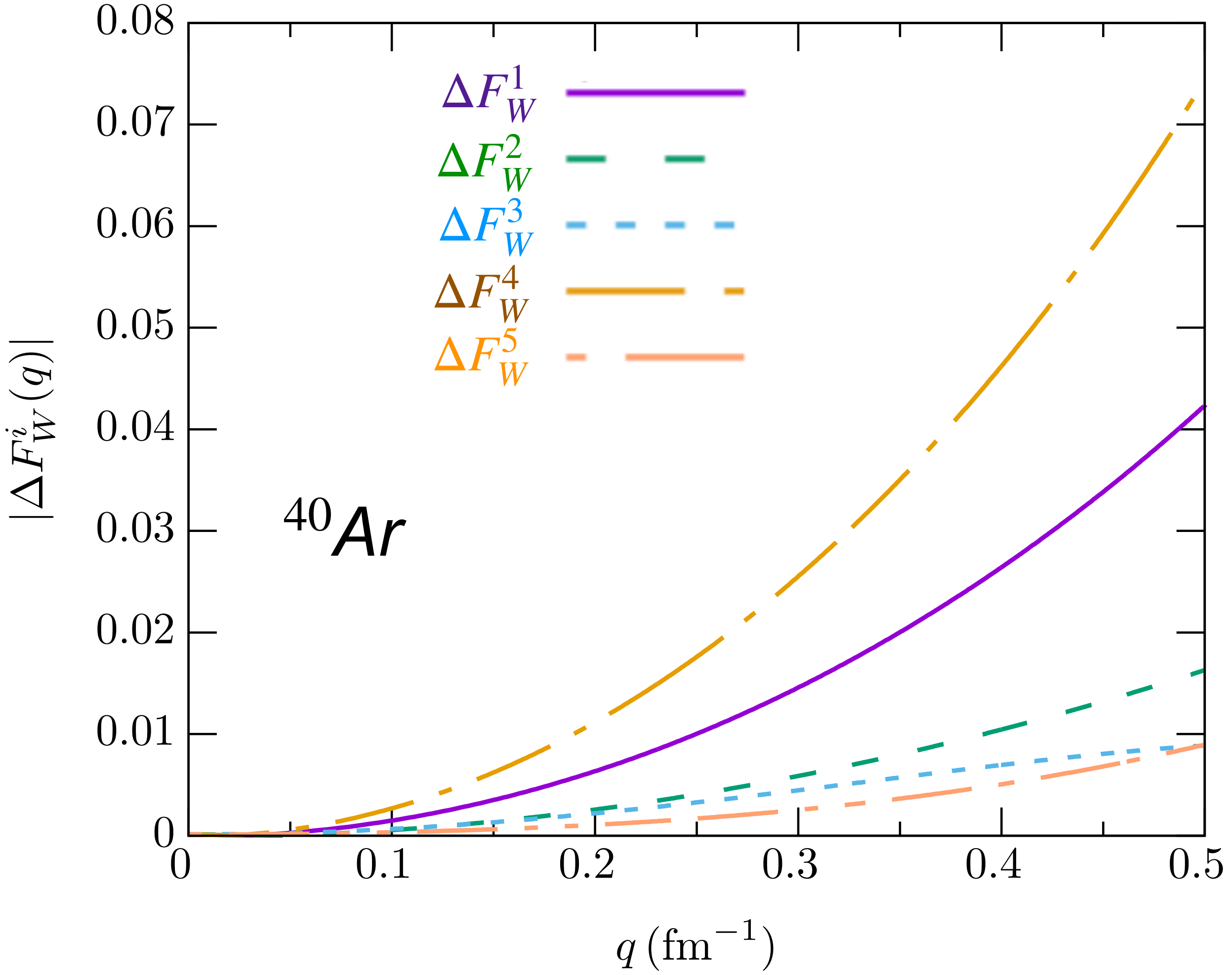


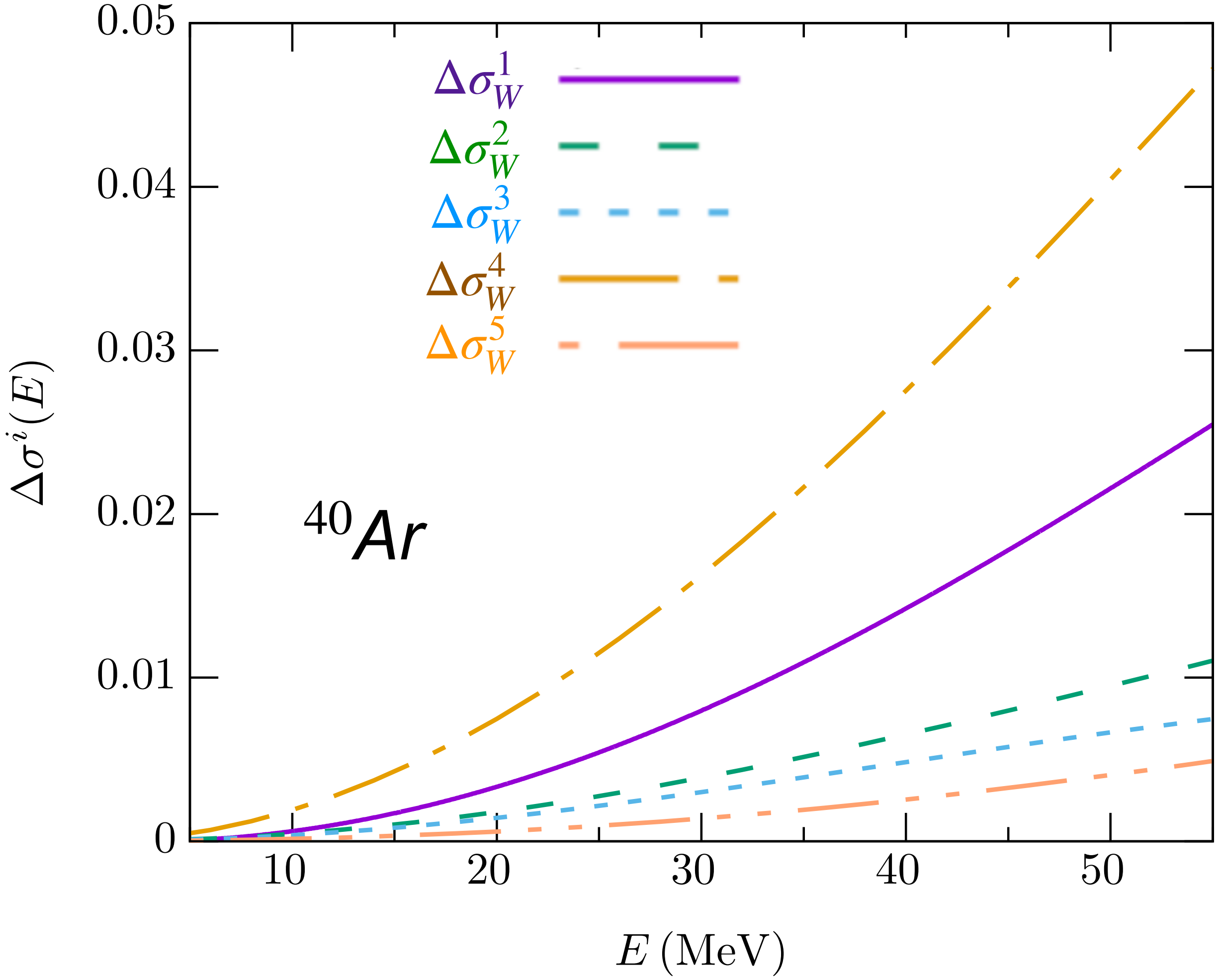


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- Over the whole $q \leq 0.5$ fm$^{-1}$ region (probed by $E \leq 50$ MeV), relative differences rise to $\lesssim 7\%$.
- The differences rise rapidly at the higher end of q.
- Over the whole $E \leq 50$ MeV region, the relative differences amount to $\lesssim 4\%$.

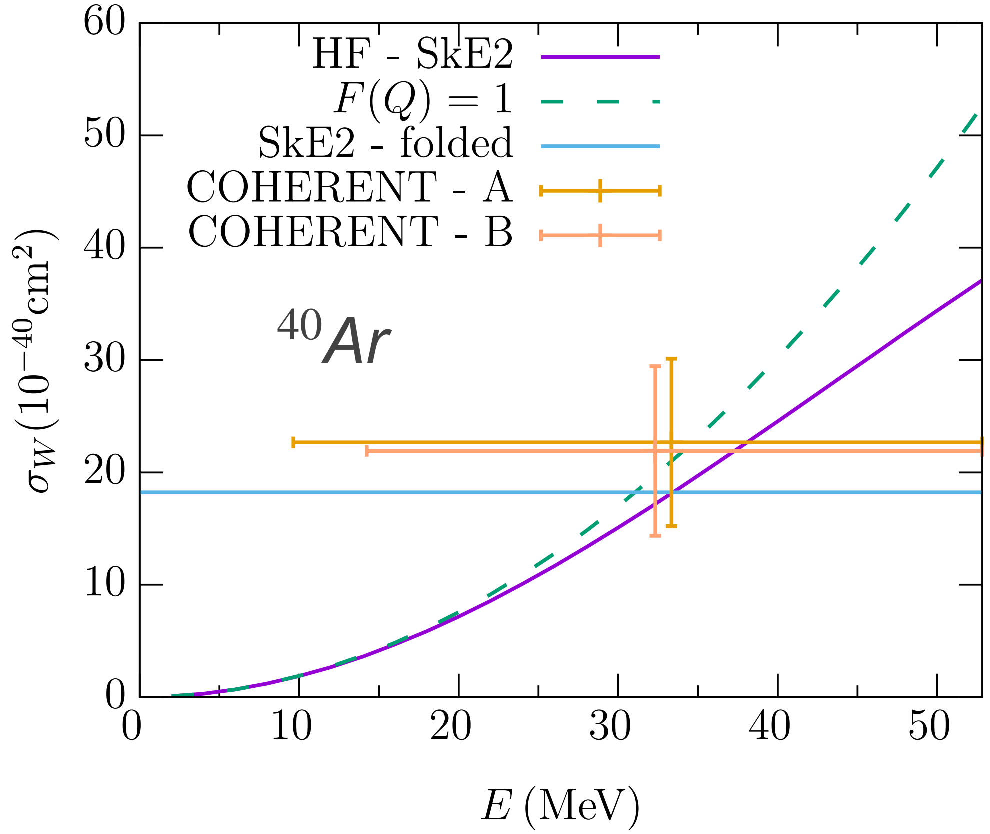
# Summary

- An accurate description of the neutron density distribution and weak form factor is vital to the CEvNS program since any experimentally measured deviation from the expected CEvNS event rate can point to new physics or to unconstrained nuclear physics.

- With no data to constrain neutron densities and weak form factors, it's crucial to treat the underlying nuclear structure physics with utmost care.

- We presented calculations of nucleon densities and form factors within a microscopic many–body nuclear theory model where the nuclear ground state is described in a Hartree–Fock (HF) approach with a Skyrme (SkE2) nuclear potential. The model describes charge form factor data remarkably well.

- We paid special attention to $^{40}$Ar, and provide an assessment of theoretical uncertainty on $^{40}$Ar weak form factor and $^{40}$Ar CEvNS cross section by comparing six different nuclear theory and phenomenological predictions.




*This work: arXiv:2007.03658 [nucl-th]*

*COHERENT: arXiv:2003.10630 [nucl-ex]*